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RADIOLOGICAL ASSESSMENT OF THE BELARUSIAN NUCLEAR POWER PLANT SITE IN THE PRE-OPERATIONAL PERIOD

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Abstract. *Field studies on the pre-operational period of a Belarusian NPP have allowed us to determine the "background" level of gamma-emitting radionuclides in individual components of the environment. The results of measuring the dose rate at the NPP construction site are from 0.048 to 0.089 μSv/h. External radiation in the surveyed area is at 96% due to* ^{40}K, ^{226}Ra *and* ^{232}Th. *The radionuclides in the surface soil layer are:* ^{40}K *– from 530 to 700 Bq/kg;* ^{226}Ra *– from 30 to 55 Bq/kg; and* ^{232}Th *– from 17 to 35 Bq/kg;* ^{137}Cs *from 2 to 13 Bq/kg. The dose rate in the floodplain of the Viliya River from 0.033 to 0.082 μSv/h. The activity concentrations of the radionuclides in the surface soil layer of the floodplain of the Viliya River are:* ^{40}K *– from 390 to 690 Bq/kg;* ^{226}Ra *– from 33 to 50 Bq/kg;* ^{232}Th *– from 15 to 50 Bq/kg;* ^{137}Cs *– from 3 to 12 Bq/kg. The activity concentration of carbon-14 and tritium in the dominant vegetation species were determined to be: from 74.4 to 111.5 pMC and less than lower range limit, respectively.*

Keywords: *Belarusian NPP, radiation monitoring, environment, dose rate, radionuclides, activity concentration*

1. INTRODUCTION

According to the recommendations of the International Atomic Energy Agency (IAEA), radiation monitoring around nuclear power plants (NPPs) at all stages in their life cycle (construction, operation, decommissioning) is necessary [1]. For each stage of the NPP life cycle, there are unique sources of radiation exposure, i.e. relevant sets of radionuclides that determine the main contribution to the exposure of a critical population group.

The selection of the site for the first nuclear power plant in the Republic of Belarus triggered large-scale and comprehensive environment assessments in the Ostrovets district of the Grodno region [2] and in neighboring countries (mainly Lithuania) [3]. The comprehensive environmental monitoring program includes hygienic parameters for assessing radiation doses and the control of ecological contamination. Soil [3], bottom riverbed sediments [3,4], surface water [5] and the atmospheric boundary layer [6] can be selected as objects of environmental studies. The main technogenic radionuclides present in discharges, emissions and radioactive waste during the operation of nuclear power plants, as well as natural radionuclides, have been selected as controlled parameters [7,8]. The inclusion of natural radionuclides in the control program is done not only because of the need to consider "background" radiation exposure, but also because there is an opportunity to use the radionuclide ratio method to identify sources of radioactive substances in the environment [9,10].

Systematic observations of the radiation characteristics of the environment, starting from the stage of choosing a construction site, allow us to obtain a relevant assessment of the radiation impact at each stage in the life cycle of a nuclear power plant. Analysis of the source data and research planning can have a significant impact on the volume and quality of the results. As such, it is necessary to consider [1]:

· the estimated characteristics of the sources of emissions, discharges and radioactive waste, including the composition of radionuclides and their physical and chemical form;

· the composition of radionuclides in the environment at the time of the construction of the nuclear power plant;

· radionuclide transfer mechanisms in environments, the characteristics that affect transfer and seasonal changes;

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· possible critical population groups.

As a result of nuclear transformations, hundreds of radionuclides are formed in the reactor core, but only a limited number of them can have an effect on the population and the environment through emissions, discharges and the generation of radioactive waste [11-16]. Radioactive substances entering the environment can be in solid, liquid or gaseous states [17,18]. The radionuclides which need to detected in order to ensure the safety of the population include a number of difficult-to-detect beta-emitting radionuclides (^{3}H, ^{14}C, ^{90}Sr), the measurement of which requires sophisticated methods for detecting and preparing samples. These cannot be realized in the field [19-22].

The presence of gamma-emitting radionuclides in relation to radiation control allows us to employ field monitoring methods that ensure speed when obtaining data. Field spectrometers, portable dosimeters and radiometers for pedestrian gamma surveys allow for detailed studies to be carried out in local areas. In turn, mobile radiation scanning systems provide significant coverage of the survey areas. The pre-operational studies carried out in the Ostrovets district made it possible to obtain the radioecological characteristics of the environment (activity concentrations of gamma-emitting radionuclides, tritium and carbon-14, ambient dose equivalent rate) for use in predicting public exposure to discharges of radioactive substances during normal operation of the NPP.

2. Materials and methods

2.1. Measurement of gamma-emitting radionuclides

A gamma spectrometric survey of the site around the Belarusian NPP was carried out on a regular grid of 100 m to 200 m (Fig. 1).

Figure 1. Points in the gamma spectrometric survey.

To take the measurements, a MKS-AT6101DR spectrometer with a scintillation counter was selected. This spectrometer can determine the activity concentrations (AC) of natural radionuclides (^{40}K, ^{226}Ra, ^{232}Th), as well as ^{134}Cs and ^{137}Cs. In addition, the MKS-AT6101DR spectrometer has functions for measuring the ambient equivalent dose rate and for GPS-binding the measurement points. The data from the spectrometer was verified by duplicating measurements with portable MKS-AT6102A and MKS-AT6101C spectrometers with scintillation counters. To study the in-situ content of gamma-emitting radionuclides in water and riverbed sediments, a MKS-AT6104DM immersion gamma spectrometer was used. The measurements were supplemented with an automotive gamma survey using a MKS-AT6101C radiation scanning spectrometer with GPS-referenced measurement points, which allowed for the expansion of the studied area.

The data accuracy of the in-situ assessment of radionuclide content was confirmed by sampling soil up to 30 cm deep and subsequent laboratory studies on the radionuclide content. The location of the sampling points is shown in Fig. 2. Taking into account the maximum value of the dilution factor due to long-term meteorological conditions, a “critical point” was determined - the area where the maximum radiation effect from emissions of radioactive substances from the NPP is realized by all irradiation paths (point 1 in Fig. 2).

To study the riverbank in three regions of the Viliya River, each 1 km long (Fig. 3), field spectrometry was used. Region 1 is located below the mouth of the Polpe River. Region 2 is located below the water extraction point for the needs of the nuclear power plant, but above the discharge point of the industrial storm drainage (ISD) of the NPP. Region 3 is located below the discharge point of the ISD. In each region, 11 gamma spectrometric measurements of the riverbed were performed. The gamma spectrometric measurement of the water in 4π geometry was possible only at four points where the depth of the Viliya River exceeded 1.5 m.

Figure 2. Location of soil sampling points.

In each region of the Viliya River, at least 11 gamma spectrometric measurements of the river bank were taken, along with one water sample and one riverbed sediment sample. Gamma spectrometric studies of the riverbank regions were carried out simultaneously with several portable MKS-AT6101DR, MKS-AT6102A and MKS-AT6101S spectrometers.

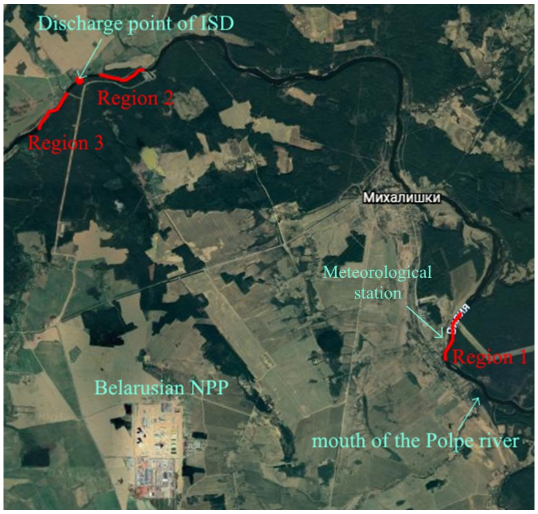

Figure 3. Location of the survey sites on the Viliya River.

2.2. Carbon-14 and tritium measurments

To measure the activity concentration of carbon-14 and tritium, the dominant vegetation species were sampled at several sites around the territory of the Belarusian NPP (Table 5).

For determining the activity concentration of tritium, selected vegetation samples were prepared for liquid scintillation counting via a Sample Oxidizer [23]. The samples were burned in an oxygen atmosphere.

The prepared samples were then measured using a Quantulus liquid scintillation counter.

Radiocarbon analysis was carried out with an accelerator mass spectrometer by Novosibirsk AMS Golden Valley staff. 16 samples of green plant mass were sent for radiocarbon analysis. The samples were dried at 50 °C to a constant weight, crushed, and sent for carbonization and further analysis with an accelerator mass spectrometer (AMS) [24-25].

3. Results

The practice of operating nuclear power plants in Russia demonstrates that discharges and emissions have a negligible radiation impact on the population and the environment. Nevertheless, the release of long-lived radionuclides into the environment can lead to local anomalous content in various environmental objects [13-14]. Atmospheric emissions form an uneven distribution of radionuclides over the area. As a result of migration processes, radioactive substances are deposited in various soil layers and accumulate in vegetation and living spaces. Discharges lead to the accumulation of radionuclides in riverbed sediments and aquatic and coastal flora and fauna.

The investigated properties of the surface distribution of the activity density of precipitated radionuclides show [26]:

· the continuity of the function characterizing the distribution of activity density over the surface in the area of deposition;

· the independence of the variability of the data sets from the size of the unit of sampling scale;

· quasistationarity – the duration over time of the change in the function of the distribution of activity density over the surface.

The main consequence of the established properties of the surface distribution of the activity density of precipitated radionuclides is that an assessment of the radiation situation in specific areas should not be limited to the assessment of the arithmetic means of measured values. A study of statistical characteristics (determination of the distribution function) obtained data on dose rate, activity concentraton, surface activity density, etc., is required for specific sites. In other words, it is necessary to search for the family of distributions that best describes the samples of the received data. According to the data obtained as a result of the Chernobyl sediment survey, an approximate model of activity density samples for a certain class of sites is a family of lognormal distribution.

In the present work, a field gamma spectrometric method (in situ) was chosen for the survey, which ensures obtaining a sufficient amount of data for a statistically reliable determination of the surface distribution function of gamma emitting radionuclides. The use of sites for in-situ measurements during rapid assessments provides quick information on fresh precipitation. The distribution of the results obtained can be represented as the sum of two lognormal distributions (Fig. 4). This multimodality can be explained by differences in road surfaces (unpaved and asphalt). Equally, the second distribution peak may be due to increased ^{40}K content on fertilized lands intended for agricultural use. Table 1 presents the parameters of the obtained distributions, indicating the number of results above the conditional threshold of 0.07 and 0.08 µSv/h.

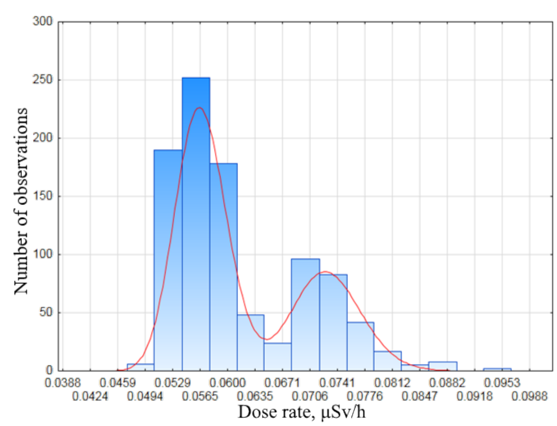

Figure 4. Distribution of the results of the automotive gamma survey.

Table 1. Parameters of the distribution of dose rate values according to the results of the automotive gamma survey

	1	2
Arithmetic mean, μSv/h	0.057	0.074
Geometric mean, μSv/h	0.057	0.074
Sigma LN	0.06	0.06
Percentage higher 0.07 μSv/h	0.02 %	80.6 %
Percent. higher 0.08 μSv/h	-	8.06 %
Number of observations	691	260

The results of pedestrian gamma surveys around the perimeter of the Belarusian NPP site are presented in Fig. 5 and Table 2. Fig. 6 and Table 3 demonstrate the results of a gamma survey on the bank of the Viliya River in a 1 km zone below the water intake point, discharge point and monitoring section below the confluence of the Polpe River.

Table 2. Parameters for the distribution of dose rate values according to the results of the pedestrian gamma survey.

Arithm. mean, μSv/h	Geom. mean, μSv/h	sigma LN	Percent. higher 0.07 μSv/h	Percent. higher 0.08 μSv/h
0.066	0.066	0.12	30.92%	5.36%

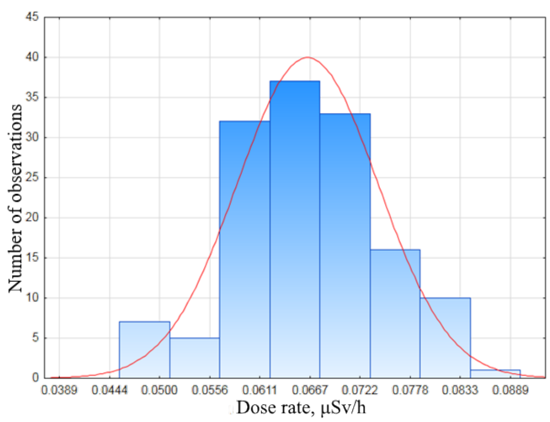

Figure 5. Distribution of the results of the pedestrian gamma survey.

Table 3. Parameters for the distribution of dose rate values according to the results of gamma surveys of the bank of the Viliya River.

Arithm. mean, μSv/h	Geom. mean, μSv/h	sigma LN	Percent. higher 0.07 μSv/h	Number of observati ons
0.043	0.042	0.15	0.04%	62

As a result of the pedestrian gamma spectrometric survey around the perimeter of the site of the Belarusian NPP (including the control site) and the bank of the River Vilya, the average value of the dose rate was determined at a level of 67 ± 8 nSv/h.

The results of dose rate measurements using the MKS-AT6101DR and MKS-AT6102 spectrometers were obtained by placing them on the surface of the earth, that is, on the interface between two media: air and soil. A correlation between the dose rate and the activity concentration of individual radionuclides is preserved in different areas of the gamma spectrometric survey, which indicates a homogeneous radio-geochemical spectrum (and indirectly indicates the homogeneous lithogenic composition of the upper geological section) (Fig. 7).

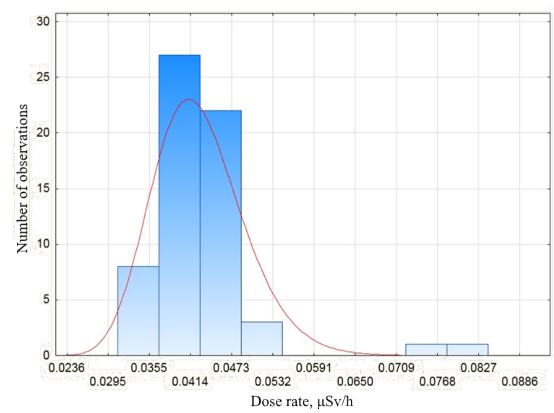

Figure 6. Distribution of the obtained gamma results from the bank of the Viliya River.

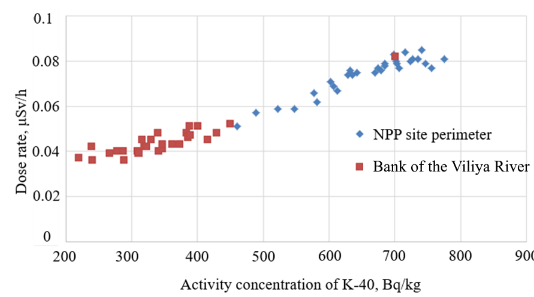

Figure 7. Correlation between dose rate and the activity concentration of ^{40}K at different sites in the gamma spectrometric survey

The results of measuring the activity concentration of radionuclides in soil samples and riverbed sediments are presented in Table 4.

The obtained values of the activity concentration for ^{137}Cs in the selected soil samples around the Belarusian NPP are less than lower range limit of the field spectrometers used in the work (50 Bq/kg). The reliability of the data obtained can be based on a comparison between in-situ results and laboratory measurements of ^{40}K, ^{226}Ra and ^{232}Th activity. The measurements were carried out using a scintillation gamma spectrometer in 4π geometry. The data in the tables on the content of natural radionuclides completely coincide with the results of the in-situ measurements. Thus, the results of all the in-situ measurements demonstrated that ^{137}Cs content is below 50 Bq/kg: this was also confirmed by the results of laboratory studies on the soil samples taken from the gamma spectrometric survey.

All the results of the field measurements of the dose rate and activity concentrations of radionuclides do not contradict observational data obtained during special studies on the construction site of the Belarusian nuclear power plant [27].

Table 4. Results of measuring the activity concentrations of ^{40}K, ^{137}Cs, ^{226}Ra, ^{232}Th in soil samples and bottom sediments.

Sample name	Activity concentration, Bq/kg			
	^{40}K	^{137}Cs	^{226}Ra	^{232}Th
Critical point				
0-10 cm	555.6±21.7	7.6±3.3	33.3±3.2	19.5±2.5
10-20 cm	580.9±22.7	7.3±3.5	35.6±3.4	21.5±2.8
20-30 cm	580.2±23.2	8.2±3.8	36.7±3.5	19.3±2.9
Lower right section	598.8±22.2	7.4±3.4	33.4±3.2	26.6±2.6
Lower left section	572.1±27.4	8.3±4.3	35.3±4.2	20.9±3.3
Field				
Plowed	679.0±22.4	5.2±3.5	37.4±3.4	29.3±2.7
Unplowed	685.6±28.1	6.2±3.8	51.3±4.2	31.6±2.9
Viliya River				
Above discharge point	666.4±22.0	6.7±3.5	44.6±3.3	37.1±2.7
Below discharge point	411.4±20.1	8.4±3.4	36.9±3.1	17.2±2.6
Markuny village, downstream of Polpe	558.9±19.1	6.1±3.5	35.9±3.2	27.6±2.2

Table 5. Tritium and radiocarbon content of selected vegetation samples

Region	Sample	^{14}C content, pMC	^{3}H content, Bq/g
Critical point	Silver birch	111.5±4.4	<2.42
	Stinging nettle	104.0±4.3	<2.05
	Lupinus	103.8±3.0	<1.64
	Perforate St John's-wort	103.4±4.8	<2.10
	Oak	102.8±2.1	<2.15
Release point of NPP	Oak	115.0±3.0	<2.57
	Alder	106.9±4.5	<2.37
	Tilia	112.0±1.0	<2.53
	Pine	98.1±2.4	<1.90
	Silver birch	93.0±0.7	<2.57
Viliya River above and below the release point of NPP	Cladophora	83.3±3.6	<1.50
	Elodea	82.2±3.9	<2.90
	Potamogeton	78.9±1.1	<2.94
Viliya River at confluence of Polpe River	Elodea	83.4±2.5	<1.88
	Cladophora	75.8±1.9	<2.73
	Potamogeton	74.4±0.8	<2.89

The activity concentrations of radiocarbon and tritium content in different samples are presented in Table 5. For terrestrial plants, the ^{14}C content is close to the modern carbon level – 100 pMC (0.227 Bq/g C). The ^{14}C content in some trees slightly exceeds this level. This may have been caused by different physiological processes in different trees. For aquatic plants, these values may be lower due to the reservoir effect resulting from the presence of a large amount of carbonates in water.

4. Conclusion

The implementation of a comprehensive field research program in the territory potentially affected by a Belarusian nuclear power plant made it possible to assess the radiation situation in the area during the pre-operational period. In this work, the assessment of the "zero background level" meant determining important parameters characterizing the radiation situation before the start of operations at the Belarusian NPP. These parameters are:

· the photon radiation dose rate (μSv/h) in the territory adjacent to the nuclear power plant, at the critical point location site and on the banks of the River Viliya;

· the content of gamma-emitting radionuclides (activity concentrations, Bq/kg) in the soil, water and riverbed sediments of the examined sections of the River Viliya;

· the carbon-14 content in the dominant vegetation species at different sites around the Belarusian NPP.

As a result of the pedestrian gamma spectrometric survey at 158 points around the perimeter of the site of the Belarusian NPP (including the "critical" point), the ranges of variation of the measured parameters were established:

· a dose rate from 0.048 to 0.085 μSv/h. A measurement of near-background dose rate levels below 0.1 μSvh for the measuring instruments used is described in publications [28-30] in accordance with the requirements of IEC 60846-1 and 61017 [31,32];

· activity concentrations of ^{40}K (natural radionuclide) – from 530 to 700 Bq/kg;

· activity concentrations of ^{226}Ra (natural radionuclide) – from 30 to 55 Bq/kg;

· activity concentrations of ^{232}Th (natural radionuclide) – from 17 to 35 Bq/kg;

· activity concentrations of ^{137}Cs (technogenic radionuclide) at all measured points are significantly lower than 50.0 Bq/kg.

· activity concentrations of ^{14}C (natural radionuclide) – from 74.4 to 115.0 pMC;

· activity concentrations of ^{3}H (natural radionuclide) – less than lower range limit.

The results of the automotive gamma surveys at 951 points remote from the site of the Belarusian NPP generally coincide with the range of dose rate values (from 0.049 to 0.093 μSv/h) from the pedestrian survey results, but differ in the terms of the bimodality of the shape of the distribution function of the repeatability of the results (Fig. 7). The presence of two modes is explained by the difference in the road surfaces (dirt and asphalt) on which the car moved during the survey.

The field gamma-spectrometric survey at 33 points of the bank of the Viliya River made it possible to reliably determine the ^{40}K content (natural radionuclide) at a range from 220 to 701 Bq/kg, the dose rate being from 0.033 to 0.082 μSv/h. The determination of the activity concentration values of ^{226}Ra and ^{232}Th in the selected areas during the field measurement phase was difficult due to the water content: the values were obtained later as a result of laboratory studies on the selected samples. The gamma-spectrometric survey of the riverbed sediments at 33 points of the Viliya River in three selected areas allowed us to reliably determine the ^{40}K content (natural radionuclide) at a range from 357 to 745 Bq/kg. The activity concentrations of ^{137}Cs (technogenic radionuclide) at all measured points on the riverbank and bed is significantly lower than 50.0 Bq/kg.

Processing the obtained data during the expedition allowed us to obtain the functions of the distribution of the dose rate and the activity of the radionuclides for all the examined sites. A change in the established ranges of values or a change in the established forms of the functions of dose rate distributions of the obtained values will mean a change in the radioecological situation caused by an external factor.

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